

# SuperB and BelleII prospects on direct $CP$ violation measurements

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## 1 Introduction

The  $CP$  violation observed in quark sector is explained by a irreducible complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix[1] in the Standard Model. One of the unitarity constraints of the CKM matrix is given by the equation  $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$  which is represented by a triangle in the complex plane. The phase can be determined from measurements of the three angles and sides of the triangle. The angles are called as  $\alpha/\phi_2 = \text{Arg}[-(V_{td}V_{tb}^*)/(V_{ud}V_{ub}^*)]$ ,  $\beta/\phi_1 = \text{Arg}[-(V_{cd}V_{cb}^*)/(V_{td}V_{tb}^*)]$  and  $\gamma/\phi_3 = \text{Arg}[-(V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*)]$ . The latest results of the measurements of sides and angles are shown in the Fig.1.

The angle  $\gamma/\phi_3$  is the least well determined among all angles. The measurement of  $\gamma/\phi_3$  had been proposed to use the process  $B \rightarrow D^{(*)}K^{(*)}$  involved with interference with  $b \rightarrow u$  and  $b \rightarrow c$  quark transition in the discussion of direct  $CP$  violation[2]. The measurement of  $\gamma/\phi_3$  is performed in a theoretically cleanly way since only the tree-dominated decays are involved. Some methods to extract  $\gamma/\phi_3$  had been suggested so far: GLW[3], ADS[4], Dalitz[5, 6] analyses. The GLW analysis uses  $D^0$  and  $\bar{D}^0$  decay into  $CP$  eigenstates such as  $K^+K^-$  or  $K_S\pi^0$ , etc. The observables of double ratio and asymmetry are defined as below:

$$\begin{aligned} R_{CP\pm} &\equiv 2 \frac{\mathcal{B}(B^- \rightarrow D_{CP\pm}K^-) + \mathcal{B}(B^- \rightarrow D_{CP\pm}K^-)}{\mathcal{B}(B^- \rightarrow D^0K^-) + \mathcal{B}(B^- \rightarrow \bar{D}^0K^-)} \\ &= 1 + r_B^2 \pm 2r_B \cos \delta_B \cos \phi_3 \end{aligned} \quad (1)$$

$$\begin{aligned} A_{CP\pm} &\equiv \frac{\mathcal{B}(B^- \rightarrow D_{CP\pm}K^-) - \mathcal{B}(B^+ \rightarrow D_{CP\pm}K^+)}{\mathcal{B}(B^- \rightarrow D_{CP\pm}K^-) + \mathcal{B}(B^+ \rightarrow D_{CP\pm}K^+)} \\ &= \pm 2r_B \sin \delta_B \sin \phi_3 / R_{CP\pm} \end{aligned} \quad (2)$$

where the  $D_{CP\pm}$  is the  $D$  meson reconstructed in the  $CP$ -even(+) or  $CP$ -odd(-) final state,  $r_B$  is the ratio of amplitudes between  $B^- \rightarrow \bar{D}^0K^-$  and  $B^- \rightarrow D^0K^-$  defined

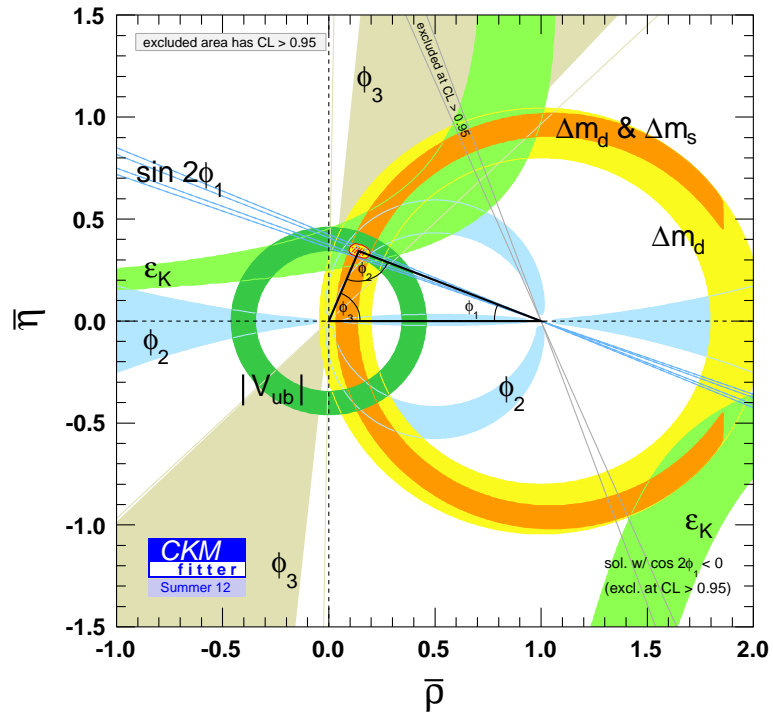


Figure 1: *The unitarity triangle.*

as  $r_B \equiv |A(B^- \rightarrow \overline{D}^0 K^-)|/|A(B^- \rightarrow D^0 K^-)|$ , and  $\delta_B$  is the difference of strong phase for these amplitudes.

The ADS analysis uses  $B^- \rightarrow D^{(*)} K^{(*)-}$  decays followed by the Cabibbo-favored(CFD) and doubly Cabibbo-suppressed  $D^0$  decays(DCSD), where the interfering amplitudes have comparable magnitude. The CFD(DCFD) decays of the  $D$  meson that can be used for ADS are  $D^0 \rightarrow K^- \pi^+$ ,  $K^- \pi^+ \pi^0$  ( $D^0 \rightarrow K^+ \pi^-$ ,  $K^+ \pi^- \pi^0$ ), etc. The observables, double ratio and asymmetry, are defined as below.

$$\begin{aligned} R_{ADS} &\equiv \frac{\mathcal{B}(B^- \rightarrow [f]_D K^-) + \mathcal{B}(B^+ \rightarrow [\overline{f}]_D K^+)}{\mathcal{B}(B^- \rightarrow [\overline{f}]_D K^-) + \mathcal{B}(B^+ \rightarrow [f]_D K^+)} \\ &= \frac{r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D) \cos \phi_3}{1} \end{aligned} \quad (3)$$

$$\begin{aligned} A_{ADS} &\equiv \frac{\mathcal{B}(B^- \rightarrow [f]_D K^-) - \mathcal{B}(B^+ \rightarrow [\overline{f}]_D K^+)}{\mathcal{B}(B^- \rightarrow [\overline{f}]_D K^-) + \mathcal{B}(B^+ \rightarrow [f]_D K^+)} \\ &= \frac{2r_B r_D \sin(\delta_B + \delta_D) \sin \phi_3 / R_{ADS}}{1} \end{aligned} \quad (4)$$

where  $r_D = |A(D^0 \rightarrow f)/A(\overline{D}^0 \rightarrow f)|$  and  $\delta_D$  is strong phase difference between  $\overline{D}^0 \rightarrow f$  and  $D^0 \rightarrow f$ .

The Dalitz analysis with  $D$  meson decay into the three-body decay  $K_S h^+ h^-$  to extract the angle  $\gamma/\phi_3$ , where  $h^\pm$  represents charged light hadrons such as pion and kaon. The model-dependent Dalitz analysis uses the isobar model [7] which assume that the three-body decay of the  $D$  meson proceeds through the intermediate two-body resonances. The total amplitude over the Dalitz plot can be represented as the sum of two amplitudes for  $D^0$  and  $\overline{D}^0$  decays into the same final state  $K_S h^+ h^-$  as below.

$$f_{B^+} = f_D(m_+^2, m_-^2) + r_B e^{\pm i\phi_3 + i\delta_B} f_D(m_-^2, m_+^2) \quad (5)$$

where  $m_+^2 = m_{K_S h^+}^2$ ,  $m_-^2 = m_{K_S h^-}^2$ . The  $f_D(m_+^2, m_-^2)$  consists of the sum of intermediate two-body amplitudes and a single non-resonant amplitude as follows.

$$f_D(m_+^2, m_-^2) = \sum_{j=1}^N a_j e^{i\xi_j} \mathcal{A}_j(m_+^2, m_-^2) + a_{NR} e^{i\xi_{NR}} \quad (6)$$

Where  $a_j$  and  $\xi_j$  are the amplitude and phase of the matrix element,  $\mathcal{A}_j$  is the matrix element of the  $j$ -th resonance, and  $a_{NR}$  and  $\xi_{NR}$  are the amplitude and phase of the non-resonant component. The  $r_B e^{\pm i\phi_3 + i\delta_B}$  can be converted to the Cartesian parameters  $x_\pm = r_\pm \cos(\pm\phi_3 + \delta)$  and  $y_\pm = r_\pm \sin(\pm\phi_3 + \delta)$ . The  $x_\pm$  and  $y_\pm$  are actual fitted parameters.

The precision of  $\gamma/\phi_3$  measurement has progressed as the data accumulated at  $B$ -factories and new efficient physics methods and analysis techniques were developed.

Although current statistics of  $e^+e^-$  colliders is over the 1.2 billion  $B\bar{B}$  pairs, it is insufficient for reliable  $\gamma/\phi_3$ . The SuperB[8] and BelleII[9] projects are planned to accumulate the 50-75 times larger than at the  $B$ -factories with improved detectors in the next decade.

## 2 $\gamma/\phi_3$ determination

The current most precise determination of  $\gamma/\phi_3$  have been performed with Dalitz method. The  $\gamma/\phi_3$  results of an model-dependent unbinned Dalitz method by Belle and BaBar are  $\gamma/\phi_3 = (78.4^{+10.8}_{-11.6} \pm 3.6 \pm 8.9)^\circ$  [10],  $(68 \pm 14 \pm 4 \pm 3)^\circ$  [11] with modulo  $180^\circ$ , respectively, where the 3rd error is the model uncertainty. The model-dependent measurement is likely to become dominated by the model uncertainty in the Super  $B$ -factories era. The new technique using model-independent binned Dalitz method [12, 13] is reported by Belle [14] is supposed to eliminate this uncertainty. The model-independent Dalitz plot is divided into  $2N$  bins symmetrically under the exchange  $m_-^2 \leftrightarrow m_+^2$ . The bin index  $i$  ranges from  $-N$  to  $N$  excluding 0. The expected number of events in bin  $i$  of the Dalitz plot of the  $D$  meson from  $B^\pm \rightarrow DK^\pm$  is

$$N_i^\pm = h_B [K_{\pm i} + r_B^2 K_{\mp i} + 2\sqrt{K_i K_{-i}}(x_\pm c_i \pm y_\pm s_i)] \quad (7)$$

where  $h_B$  is a normalization constant and  $K_i$  is the number of events in the  $i$ th bin of the  $K_S^0 \pi^+ \pi^-$  Dalitz plot of the  $D$  meson in a flavor eigenstate.  $x_\pm$  and  $y_\pm$  are the same parameters as the ones used in the model-dependent Dalitz analyses.

The Belle reported the first  $\gamma/\phi_3$  measurement with the model-dependent Dalitz method,  $\gamma/\phi_3 = (77.3^{+15.1}_{-14.9} \pm 4.1 \pm 4.3(c_i, s_i))^\circ$ . Here the 3rd error is the uncertainty of the strong phase determination in the Dalitz plane studied by CLEOc experiment based on  $818 pb^{-1}$  at  $\Upsilon(3770)$  [15]. Now, the BESIII [16] experiment had accumulated the  $2.9 fb^{-1}$ . The uncertainty is expected to be less than 1 degree in the near future.

The GLW and ADS combined measurements have also comparable constraints and model-independent on the  $\gamma/\phi_3$  determination in Fig.2. These measurements have a important role to determine the  $\gamma/\phi_3$  in the SuperB and BelleII era. The expected precisions are shown in the Table.1.

## 3 Direct $CP$ violation in charmeless hadronic decay

The direct  $CP$  asymmetries has been observed in two-body decays such as  $B^0 \rightarrow \pi\pi$  and  $B^0 \rightarrow K\pi$  decays. The charmless 2-body  $B$  meson decays could receive contribution from processes beyond the standard model. For example, the  $B \rightarrow K\pi$  proceeds through the suppressed tree diagram and loop penguin diagram of similar

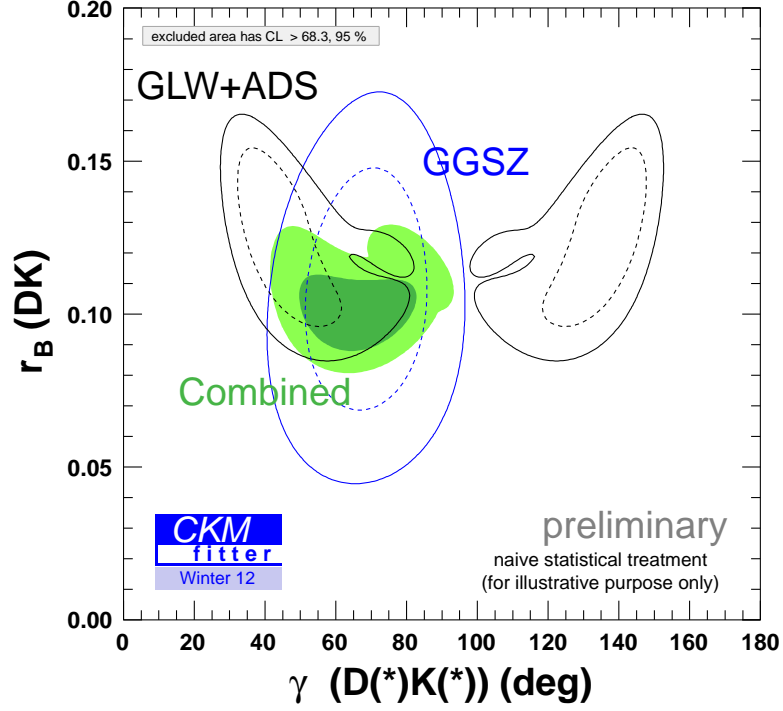


Figure 2: The correlation between the  $\gamma/\phi_3$  and the ratio of interfering amplitudes  $r_B$  of the decay  $B \rightarrow DK$  from world average  $D^{(*)}K^{(*)}$  decays (GLW+ADS) and Dalitz analyses.

Observable	$B$ Factories( $2ab^{-1}$ )	SuperB( $75ab^{-1}$ )	BelleII( $50ab^{-1}$ )
$\gamma/\phi_3(B \rightarrow DK, GLW)$	$\sim 15^\circ$	$2.5^\circ$	} $5^\circ$
$\gamma/\phi_3(B \rightarrow DK, ADS)$	$\sim 12^\circ$	$2.0^\circ$	
$\gamma/\phi_3(B \rightarrow DK, Dalitz)$	$\sim 9^\circ$	$1.5^\circ$	$2^\circ$
$\gamma/\phi_3(B \rightarrow DK, combined)$	$\sim 6^\circ$	$1-2^\circ$	$1.5^\circ$

Table 1: The expected precision of  $\gamma/\phi_3$  determination at SuperB and BelleII. Both the statistical and systematic errors are assumed to scale with the integrated luminosity.

magnitude(Fig.3). The interference of the two diagrams cause a direct  $CP$  asymmetry of  $A_{CP}^f = [\Gamma(\overline{B} \rightarrow \overline{f}) - \Gamma(B \rightarrow f)]/[\Gamma(\overline{B} \rightarrow \overline{f}) + \Gamma(B \rightarrow f)]$ .

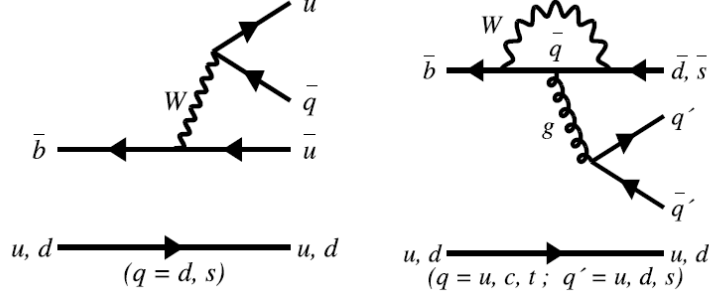


Figure 3: Tree diagram and penguin diagram in  $B \rightarrow hh$  decay.

The processes involved in the decays of neutral and charged  $B$  decays to  $K\pi$  are expected to be the same. Additional diagrams which can contribute to  $B^+$  decays shown in Fig.4 are expected to be much smaller than the contributions in Fig.3, thus, the asymmetries  $A_{CP}^{K^+\pi^0}$  in  $B^\pm\pi^0$  decays and  $A_{CP}^{K^+\pi^-}$  in  $B^0(\overline{B}^0) \rightarrow K^\pm\pi^\mp$  decays are expected to be the same. The recent averages of  $A_{CP}^{K^+\pi^0}$  and  $A_{CP}^{K^+\pi^-}$  by HFAG[17] show significant ( $5\sigma$ ) deviation of  $\Delta A_{K\pi} = A_{CP}^{K^+\pi^0} - A_{CP}^{K^+\pi^-}$  from 0. This is known as  $\Delta A_{K\pi}$  puzzle. A sum rule relation[18] in Equation.8 proposed to test the puzzle with various measured observables in  $K\pi$  decays.

$$A_{CP}^{K^+\pi^-} + A_{CP}^{K^0\pi^+} \frac{\mathcal{B}(B^+ \rightarrow K^0\pi^+)\tau_{B^0}}{\mathcal{B}(B^0 \rightarrow K^+\pi^-)\tau_{B^+}} = A_{CP}^{K^+\pi^0} \frac{2\mathcal{B}(B^+ \rightarrow K^+\pi^0)\tau_{B^0}}{\mathcal{B}(B^0 \rightarrow K^+\pi^-)\tau_{B^+}} + A_{CP}^{K^0\pi^0} \frac{2\mathcal{B}(B^0 \rightarrow K^0\pi^0)}{\mathcal{B}(B^0 \rightarrow K^+\pi^-)} \quad (8)$$

where  $\mathcal{B}(B \rightarrow f)$  denotes the corresponding branching fraction and  $\tau_{B^0(B^+)}$  life time of neutral and charged  $B$  mesons.

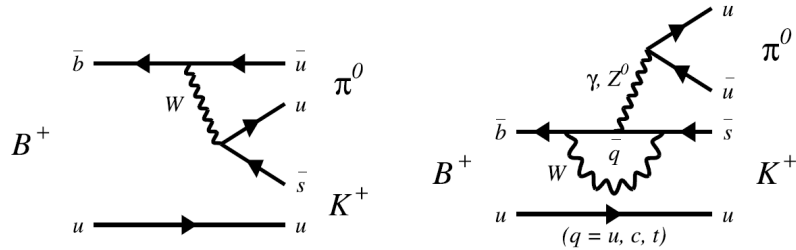


Figure 4: Color suppressed diagram and electroweak penguin diagram in  $B^+ \rightarrow K^+\pi^0$  decay.

Using the current world average values for the corresponding observables[17], the sum rule can be represented as a dependence of the least precise asymmetry  $A_{CP}^{K^0\pi^0}$  on the  $A_{CP}^{K^0\pi^+}$  as shown in Fig.5. A violation of the sum rule would indicate new physics in  $b \rightarrow \bar{q}q$  transition.

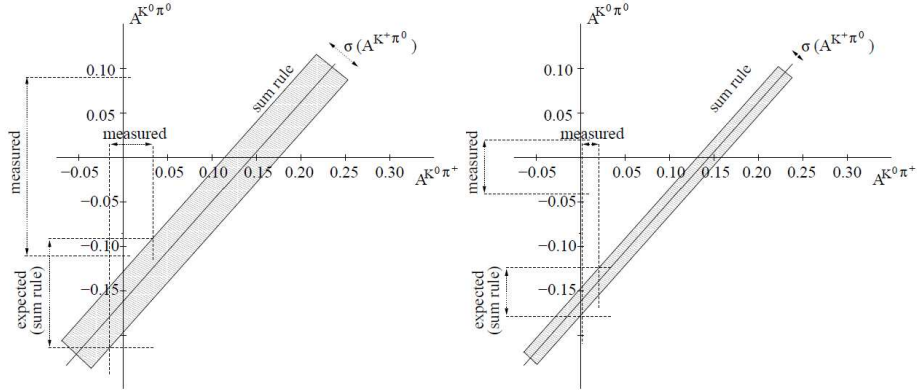


Figure 5: Current world-average constraints on  $A_{CP}^{K^0\pi^0}$  vs  $A_{CP}^{K^0\pi^+}$  [17](left). Expected constraints with the same central values and scaled for the integrated luminosity of  $L = 50 \text{ ab}^{-1}$  at the BelleII. Contribution of systematic error in the figure adapts the current systematic error without any scaling conservatively.

## 4 Conclusion

Current most precise determination of  $\gamma/\phi_3$  is brought by the Dalitz analyses. Both the model-independent and improved model-dependent analysis pushed down the systematic limitation and open up the possibilities of much higher precision determination at super  $B$  factories in near future. Furthermore, the combined ADS and GLW results have a competitive determination with the Dalitz analysis. Since the measurement of  $\gamma/\phi_3$  is obtained theoretically cleanly from the tree-dominated decays, the precise measurement will still play a important role for the test of unitarity triangle in the super  $B$  factories era.

The direct  $CP$  violation in the charmless hadronicis decay is suitable place to explore the new physics phenomena. A violation of the sum rule of  $B \rightarrow K\pi$  would indicate new physics in  $b \rightarrow \bar{q}q$  transition. The SuperB and BelleII also have good potential to search for the existence of new physics in this mode.

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